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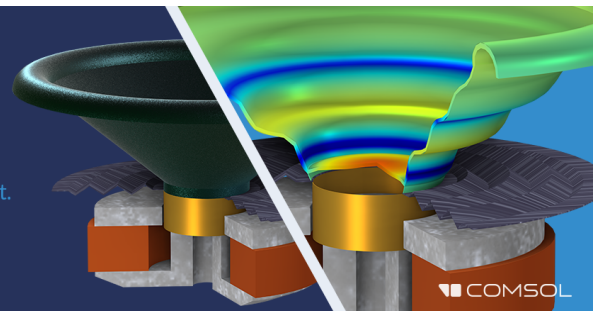
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Acoustics of the Lascaux cave and its facsimile Lascaux IV

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ABSTRACT:

Access to the original Lascaux cave, a UNESCO World Heritage site famous for its 18 000 year old paintings, has been restricted since 1963. In 2016, an accurate facsimile, Lascaux IV, was designed and built. In the original cave, Lascaux I, classical contemporary room acoustics measurement systems could not be used. However, it has been possible to perform simplified measurements in a few minutes. Similar measurements were made in Lascaux IV once completed. The data provide a unique insight of the acoustic behavior of the Lascaux cave: it shows that the two caves, the original and the copy, have similar acoustical characteristics. In both cases, in the famed Hall of Bulls, the impulse response is smooth, reverberation time is relatively long, and speech intelligibility is fair; this environment is suitable for the ceremonies that presumably took place there. Because of the precision of the copy, Lascaux IV could be used as a 1/1 scale-model of Lascaux I. Therefore, sophisticated acoustical tests could be undertaken in Lascaux IV to help specialists in their archeological investigations. For example, resonances could be precisely documented to explore the potential relationship between parietal painting positions and echoes or sound effects that may have been used in ritual ceremonies. © 2020 Acoustical Society of America.

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I. INTRODUCTION

The preservation criteria applying to the Lascaux cave in Dordogne, in southwestern France, make it impossible to perform extensive physical measurements. Therefore, the full acoustical characteristics of the cave are not known objectively. Since, according to some archeologists, the choice of the mural paintings themes and their localization may have been influenced by the acoustic behavior of the space, an objective evaluation of the acoustics of Lascaux may be useful (Ministère de la Culture s.d., 2020).

During the preliminary phase of design of Lascaux IV, a new exact copy, a short visit to the original cave Lascaux I was organized. The two visitors were equipped with calibrated smartphones and a wooden concussion idiophone. This musical instrument was used as an impulsive sound source. The impulse response was recorded in the “Salle des Taureaux” and in two other locations.

The results for the Salle des Taureaux or “Hall of Bulls” show that the impulse response bears resemblance with the response of a symphony hall with fair speech intelligibility meaning that the space is adequate for music, speech, and song.

A detailed three dimensional (3D) acoustics computer model was created and calibrated using these results to investigate various parameters. It contributed to the design

of the aesthetically identical copy of the original: Lascaux IV. Of course, for practical reasons, the materials used to build the copy could not match those of the original cave but an effort was made to duplicate as much as possible the acoustic response of the historical cave.

The same impulse response measurements were performed in Lascaux IV when it was completed with the same idiophone as impulsive source. Though the technique used does not include low frequencies, the results in both caves show similar internal acoustic properties.

II. THE LASCAUX CAVE

A. Origin of the Lascaux cave parietal art

The “Grotte de Lascaux” or Lascaux cave, a UNESCO World Heritage Site located near Montignac in Dordogne in southwestern France, contains around 400 paintings of animals, 1500 engravings, and 600 abstract drawings. The cave, which is considered as an art gallery and, at the same time, a sanctuary, was decorated about 18 000 years ago. It had been forgotten but was stumbled on by chance in September 1940.

The walls are covered with representations of animals. The various parts of the cave have been named the Hall of Bulls, the Passageway, the Shaft, the Nave, the Apse, and the Chamber of Felines. The most famous section of the cave is The Hall of Bulls with its bulls, horses, and bucks. Four black aurochs seem to be in motion (Frantova *et al.*, 2011). Cro-Magnon and his associates were extraordinary

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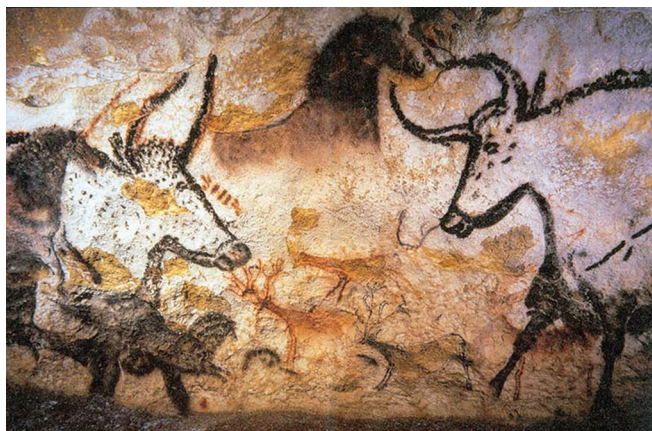


FIG. 1. Aurochs in the Hall of Bulls.

artists comparable to Raphaël or Picasso (Breuil, 1952; Bataille, 1955). (See Fig. 1.)

The cave was originally opened to visitors in 1948 but the paintings were progressively damaged by carbon dioxide, heat, humidity, and other contaminants. It had to be closed to the public in 1963; some restoration took place.

Today, only the technical staff and some scientists are allowed in for very short visits.

B. Facsimiles of the Lascaux cave: Lascaux II, III, and IV

Lascaux II, a partial copy of the Hall of Bulls and the Painted Gallery, opened in 1983 in the cave's vicinity. Lascaux III is an exhibit that has circulated worldwide. In 2016, a complete and exact facsimile called Lascaux IV was inaugurated. The interior of the facsimile was produced by the Atelier des Fac-similes du Périgord in Montignac-sur-Vézère using layers of composite materials; using advanced digital technologies, the finer details of the original cave walls were reproduced very accurately.

III. ARCHAEOACOUSTICS OF PAINTED CAVES

Scientists have attempted to understand the role that the acoustics of painted caves may have played (Kolar, 2018; Waller, 1993).

It is assumed that the localization of paintings and engravings was influenced by the acoustic response of the cave. Some signs were found that suggest focal points from which spectacular echoes can be generated from the long and narrow galleries.

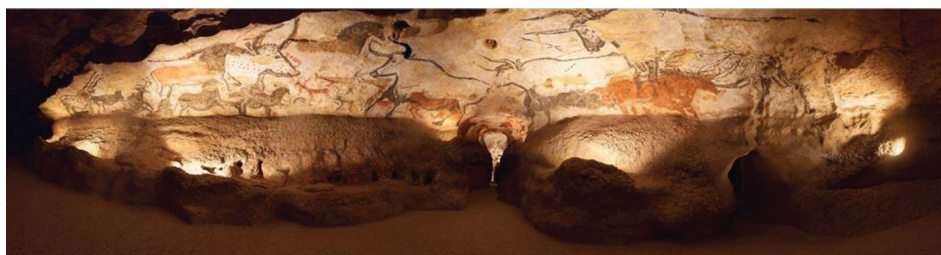


FIG. 2. Hall of Bulls.

Reznikoff (1987) and Reznikoff and Dauvois (1988) have assumed that these striking acoustical effects might have been used in rituals, sacred ceremonies, and initiations presumably enriched also by instrumental music and songs. The most powerful phenomena might have been used to generate body quiver.

Fazenda *et al.* (2017) have assembled data that demonstrate that the location of paleolithic motifs in painted caves may be related to their acoustical behavior and that the perception of remarkable sound effects may have influenced the evolution of paleolithic societies.

A. Listening to Lascaux's acoustics

Early visitors of the original Lascaux cave were impressed by some unusual acoustical effects.

They observed the relative silence in the cave, which led everyone to instinctively reduce voice levels while entering. Then the soundscape gives the impression that some animals are shouting, running, talking....

This phenomenon can be revealed by an experiment. In the Hall of Bulls, a spot marked by traces of candle drops has been identified as the possible position of a master of ceremonies. One may assume that a lit candle was placed at that spot. Emission from the same position of hand clapping provides the illusion to people present in the Hall of Bulls that the bulls are running! (See Fig. 2.)

IV. IMPULSE RESPONSE MEASUREMENTS IN THE ORIGINAL LASCAUX CAVE

Performing extensive acoustical measurements in Lascaux I, the original cave, using sophisticated instrumentation and sources is out of the question.

Therefore, at an early stage of design of facsimile Lascaux IV, a simple and quick procedure was imagined. Two of the project architects, Rune Veslegard and Frank Kristiansen, who could visit Lascaux I for a very short time, used a smartphone calibrated for linearity over an adequate frequency range to record impulsive sound signals. There were three source locations: the master of ceremonies position in the Hall of Bulls, a point in front of the great black bull in the Axial gallery, and a spot across the "Black Cow" in the Nave.

The impulse source was a clapping orchestra instrument: a concussion idiophone, sometimes called whip or slapstick. It provides a short powerful Dirac type of impulse. (See Fig. 3.)

This method does not match the rigorous requirements of contemporary acoustics measurements because they were

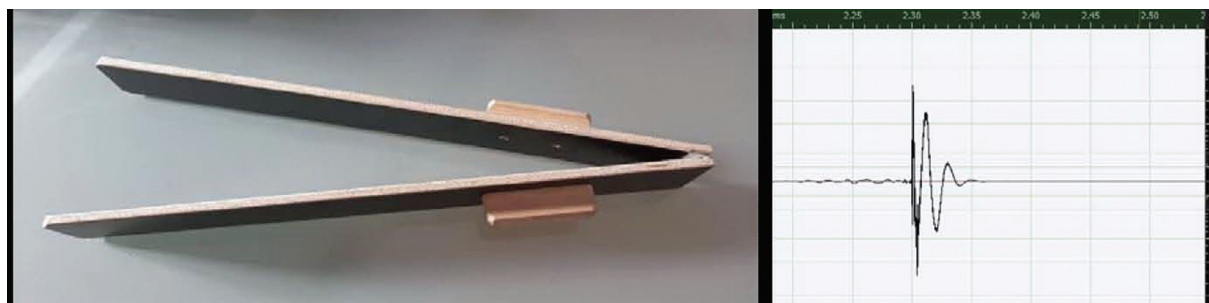


FIG. 3. Concussion idiophone and its impulse response.

performed under severe constraints; it is not reliable below the 125 Hz band.

It turns out that the concussion idiophone generates a very powerful and pure impulse; this remarkable feature simplifies the analysis of the received signal. There is no directivity data for this specific idiophone, but one can assume that omnidirectionality is adequate because of the similarity to the sound generating mechanism to that of other wooden clappers which have been shown to provide satisfactory directivity for room acoustical measurement (Sumarac-Pavlovic *et al.*, 2008).

Clearly, this procedure does not match the rigorous requirements of accurate professional contemporary measurement methods, but it is efficient enough, except at very low frequencies.

The recorded impulse can be analyzed using the techniques used currently in concert halls and opera houses and physical acoustic parameters can be calculated: reverberation time, speech intelligibility, clarity and so on. Specific

acoustical phenomena can be observed. Auralization techniques allow a convolution of anechoic voice or music recordings to create an audible model of sounds that may have existed in the cave.

A. Analysis of the measurements in the Hall of Bulls in Lascaux I

The Hall of Bulls of Lascaux I, which is probably the most famous parietal art example with a long representation of aurochs and horses, is 19 m long, from 5.5 to 7.5 m wide with a maximum height of 17 m. It leads to the Axial Gallery and to the Nave through the Passageway. (See Figs. 4 and 5.)

An example of impulse response in the Hall of Bulls is represented below. The source S has been positioned at the very spot where extraordinary sound and light effects can be generated, as explained in Sec. II A above. The response curve in the Hall of Bulls is akin to the response curve of a

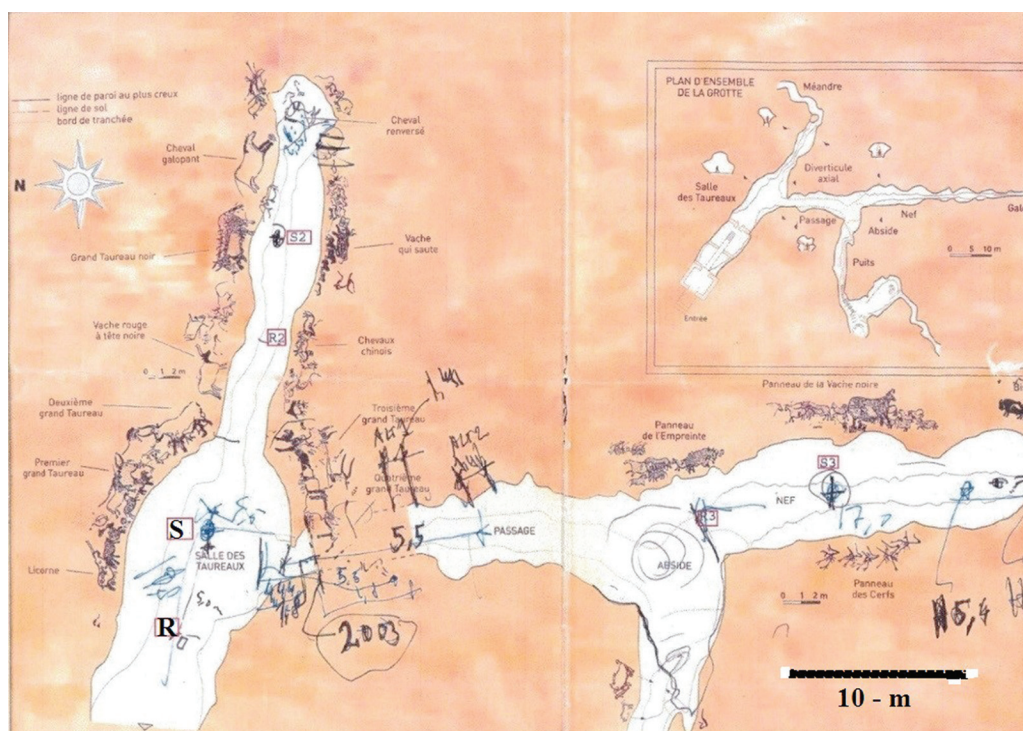


FIG. 4. Lascaux I source (S) and reception point (R) in Hall of Bulls.



FIG. 5. Hall of Bulls (Lascaux II replica).

large concert hall. This is confirmed by the values obtained for important acoustical parameters.

Reverberation time is long and it is associated with a good intelligibility; this is remarkable. It confirms that this space was adequate to create a mythical ambience and simultaneously to allow clear speech or song.

In the analysis, the steady state sound pressure levels have been adjusted to 0 dB at each frequency (Yamaha and Hidaka, 2001). (See Fig. 6 and Table I.)

B. Identification of resonances

The impulse response recordings in Lascaux I can be used to identify resonances and attempt to correlate them to archeological discoveries.

The following example identifies resonances in the 250 Hz third-octave band in the Hall of Bulls. (See Fig. 7.)

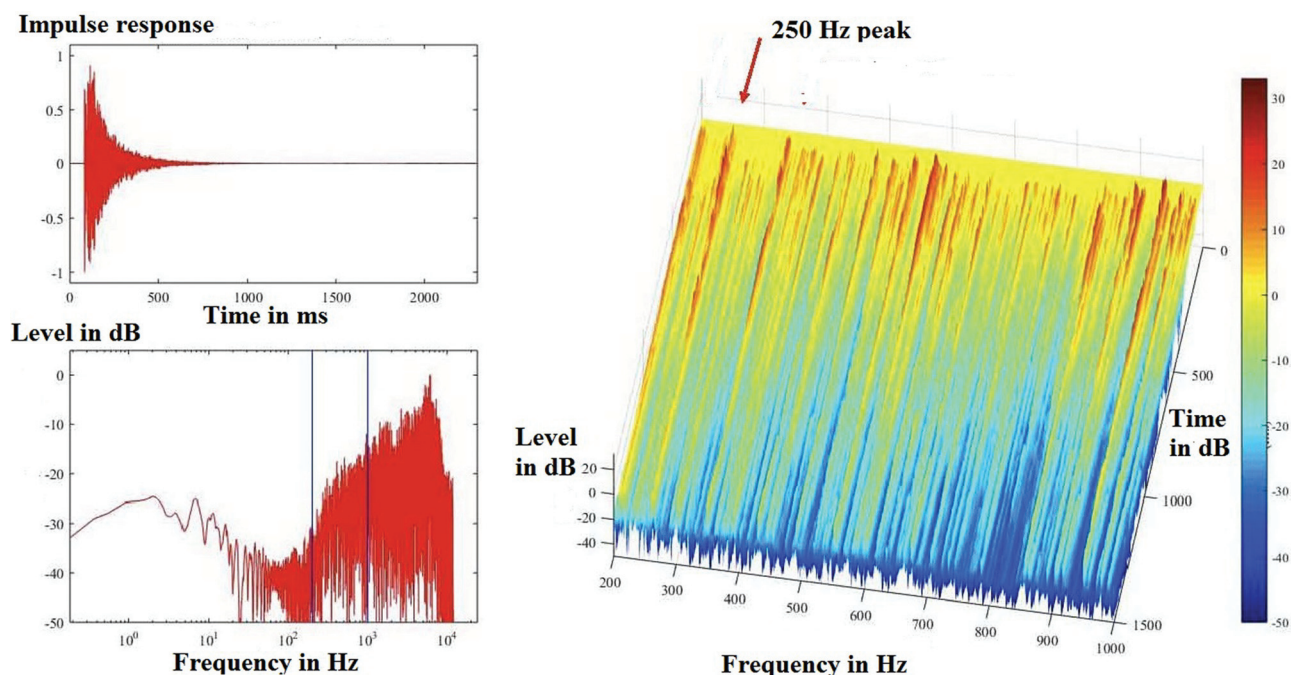


FIG. 6. Impulse response, spectrum and energy time frequency plot in the Hall of Bulls of Lascaux I.

TABLE I. Results in the Hall of Bulls of Lascaux I.

Hall of Bulls		Frequency Hz	250	500	1000	2000	4000	8000
EDT (s)	Early decay Time		2,2	2,1	1,6	1,2	0,8	0,7
RT (s)	Reverberation time		2,8	2,2	1,7	1,4	1,0	0,8
Ts (ms)	Center time		213,0	153,2	133,2	105,2	72,3	57,1
C80 (dB)	Clarity		-6,8	-1,4	-0,8	0,5	3,7	5,4
D50	Definition		0,48	0,13	0,23	0,21	0,31	0,45
Speech transmission index STI male							0,54	

C. Conclusions of measurement results in Lascaux I

In the Hall of Bulls, the acoustic response is quite remarkable: a long reverberation is associated with a good speech intelligibility and a fair clarity. The behavior is comparable to the response of a contemporary symphony hall. This means that the general ambience was that of a large temple but the spoken or sung words were intelligible while music could expand with elegance.

Reverberation is of course more moderate in the galleries. One may assume that sound effects, clapping hands for example, were quite spectacular and that late echoes could be generated from the narrow ends of the galleries.

V. THE ACOUSTICAL DESIGN OF THE FACSIMILE LASCAUX IV

In 2013, the realization of a new and more complete facsimile and of a museum was initiated. The design of such a building is complex. In such a case, acoustics is merely a secondary discipline: The weight of acoustics is negligible compared to that of other disciplines such as architecture, structure and thermal engineering, scenography, and

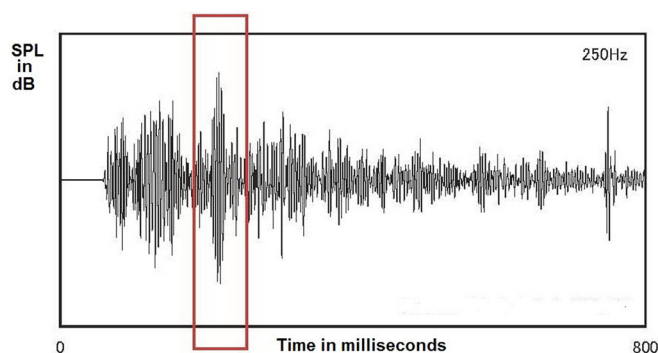


FIG. 7. (Color online) Identification of a resonance in the Hall of Bulls, 250 Hz 1/3 octave band.

economics. However, some participants were aware of the major role that sound may have played 18 000 years ago in the original cave.

The role of the acoustical scientists was to understand as much as possible the acoustical characteristics of Lascaux I. A modest but efficient research procedure, which included acoustical measurements with the most advanced measurement techniques was proposed; it was turned down for unknown reasons. However, during a single short visit of the original cave, it was possible to acquire some impulse sound recordings as described above.

It was then the duty of the acoustical engineers of the project to ensure that the acoustical behavior of the facsimile Lascaux IV was as similar as possible to that of the original despite the other very legitimate constraints of the design.

A procedure was set up to reach that goal. It consisted of the creation of an accurate acoustical computer model, to test the absorptive and diffusive properties of the materials on this model and to propose feasible adjustments to the designers.

Fortunately, the shapes and details of the inner skin were reproduced very accurately. Using sophisticated digital tools, the inner surface was surveyed with precision; composite panels reproducing the original with rigorous details were produced. The 25-mm thick material is a dense composite mortar with mineral inclusions, with a density of about 1000 kg/m³. The absorption coefficient is on the order of 0,05 at mid frequencies and 0,1 at low frequencies. The sound reduction index is 35 dB. The panels were assembled on ribbed metal frames and painted scrupulously. This remarkable work ensured that the diffusive properties inside the copy and inside the original would be almost identical.

Evidently, the materials of the new facsimile could not match exactly those of the original cave; the contaminated materials were of course not integrated in the design. Therefore, it was expected that the impulse response of Lascaux IV would be longer than the response in Lascaux I and that all the parameters would be affected accordingly.

In addition, to allow groups of visitors to enter Lascaux IV, various components which affect the acoustic response

had to be integrated: gangway, lights, air conditioning, alarm systems, etc.

The sound reduction and absorption properties of the composite material and of all the added components were evaluated. Adjustments were then proposed to other team members to refine as much as possible acoustical requirements.

The question of noise in Lascaux IV is important since, in the original cave the role of the relative silence is critical. Since the facsimile is very close to the mechanical equipment room which contains air-conditioning units and other technical devices, the acoustical insertion loss of the envelope was reinforced, and the air outlets were treated. In the mechanical equipment room and in the facsimile itself severe acoustical criteria were imposed. The noise criteria at the end of construction of 38 dB(A) in the facsimile and 45 dB(A) in the technical room were met.

A. Acoustical digital model of Lascaux I

For a better understanding of the acoustics of the Lascaux cave, a computer model was used. It was calibrated using the results of the measurements in Lascaux I. (See Fig. 8.)

VI. ACOUSTICAL MEASUREMENTS IN THE FACSIMILE LASCAUX IV

A. Measurement method

At the end of construction, before the inauguration in 2016, measurements were performed in the Lascaux IV facsimile using the same concussion idiophone as a source of impulsive sound and a Class 1 sound level meter. The analysis of the recordings used the same techniques as those used earlier in Lascaux I. The acoustical properties of Lascaux I and of Lascaux IV can be compared.

B. Lascaux IV acoustic response results

See Fig. 9 and Table II.

VII. LASCAUX I AND LASCAUX IV ACOUSTICS COMPARED

The comparison of the data acquired in Lascaux I and in Lascaux IV (see Fig. 10.) with comparable background noise levels on the order of 35 dB(A) and under similar conditions leads to the following conclusions:

- The wide-band acoustic responses of both caves are not identical but quite similar.
- One can conclude that the diffusion characteristics of both are quite close because of the accuracy of the composite surface. **The loudness frequency dependence is probably determined by the cave shape and this indicates that the shape duplication is very accurate. Similar vocal effects can be expected in both caves.**
- The inner skin is less absorptive in Lascaux IV than in Lascaux I.

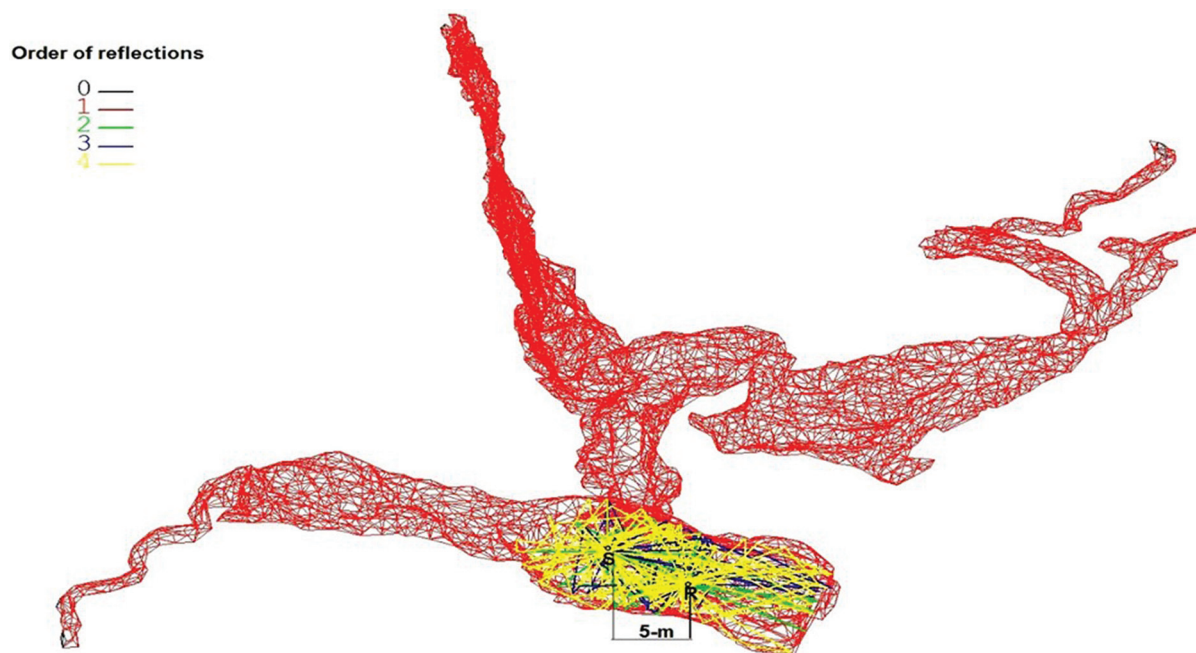


FIG. 8. Computer model of the Lascaux cave.

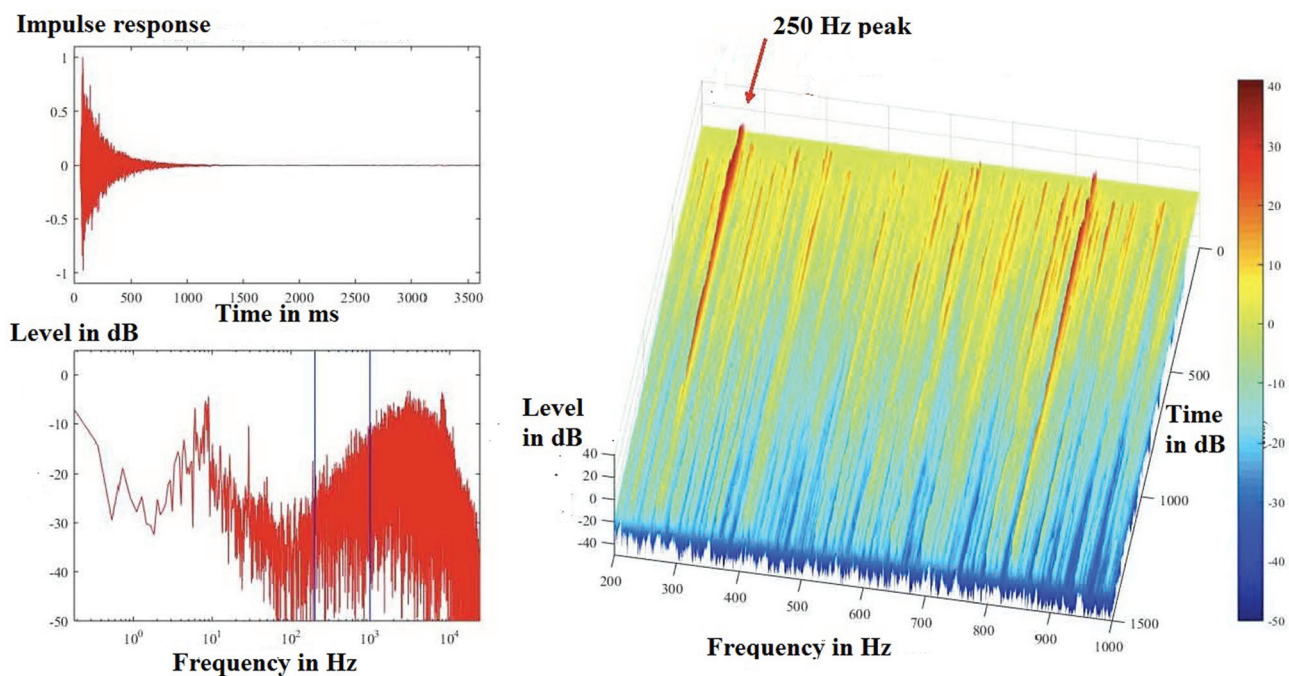


FIG. 9. Impulse response, spectrum and energy time frequency plot in the Hall of Bulls of Lascaux IV.

TABLE II. Results in the Hall of Bulls of Lascaux IV.

Hall of Bulls Lascaux IV	Frequency Hz	250	500	1000	2000	4000	8000
EDT (s)	Early decay Time	2,6	2,8	2,4	1,9	1,3	0,8
RT (s)	Reverberation time	3,0	2,7	2,3	1,8	1,4	0,8
Ts (ms)	Center time	223	215,4	191,2	161	117,6	71,9
C80 (dB)	Clarity	-5,0	-3,6	-3,5	-3,3	-0,8	3,5
D50	Definition	0,14	0,17	0,2	0,19	0,23	0,44
Speech transmission index STI male						0,45	

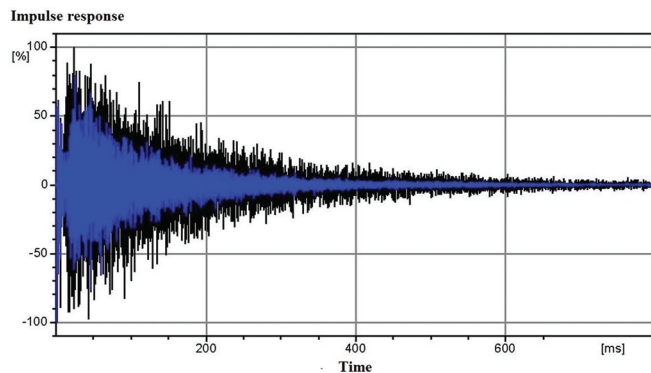


FIG. 10. Overlay of the impulse responses of Lascaux I (blue) and Lascaux IV (black).

- C80 is a very useful parameter to evaluate clarity, especially in the context of temporal masking. Here, C80, 3 (3 means the average of 500, 1k, 2k Hz) is -0.9 dB for Lascaux I and -3.5 dB for Lascaux IV. The former value means that clarity in Lascaux I is within the “excellent” range, while the latter is a little bit lower than the preferable value of -2 to 2 dB. However, one needs to consider the difference of absorptivity of the interior walls of both caves.
- The sound fields may be similar enough to allow productive experiments in Lascaux IV that would be representative of the sound distribution in Lascaux I.
- A comparison of responses in Figs. 6 and 9 indicates that, in both cases, loudness has a salient peak around 250 Hz. This detail shows that Lascaux IV simulates Lascaux I adequately in this respect. It is interesting to observe that this resonance frequency coincides with a frequency component typical of the bellow of contemporary bulls. No one knows the truth, but the acoustics of Lascaux may illustrate a missing link between the Cro-Magnon man and the Aurochs....

VIII. CONCLUSION

The results show that the acoustic responses and the speech intelligibility values in the original cave and in the copy are similar; it has been observed though that reverberation time in the “Salle des Taureaux” is slightly higher in the Lascaux IV facsimile.

The contributions of this study are the following:

- For the first time, the acoustic impulse response of the Lascaux I natural cave discovered in 1940 has been measured objectively and key acoustic parameters have been calculated.
- Similar measurements performed in the Lascaux IV facsimile lead to values that are close to those obtained in the original cave Lascaux I.
- The acoustic behavior of the original cave has been reproduced reasonably well in the facsimile. The facsimile Lascaux IV can then be used as a 1/1 acoustical scale model of the original cave Lascaux I.

Therefore, it will be possible to perform significant archeoacoustic experiments in the Lascaux IV facsimile, analyzing, for instance, the simulation by clapping of the sound of stampeding animals. A comparison will then be possible with analogous acoustical effects observed in other painted caves.

ACKNOWLEDGMENTS

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